

Semielastic Dark Matter

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Many models have recently been proposed in which dark matter (DM) couples to Standard Model fields via a GeV-scale dark sector. We consider scenarios of this type where the DM mass, at the electroweak/TeV scale, is generated by the VEV of a singlet which also couples to the Higgs. Such a setup results in a distinct recoil spectrum with both elastic and inelastic components. We construct an explicit NMSSM-like realization of this setup, discuss constraints coming from the relic density, and include benchmark points which are consistent with current limits, yet visible at upcoming direct detection experiments.

I. INTRODUCTION

By now, there is overwhelming evidence supporting the existence of particle dark matter (DM). Many models incorporate DM into proposals for new TeV-scale physics, with recent efforts focusing on the possibility that DM may also interact with a *dark sector*, composed of new gauge groups and light (GeV-scale) degrees of freedom. These models attribute positron/electron cosmic ray excesses [1] to the annihilation [2–6] or decay of [7, 8] of DM via the new GeV-scale states. In effect, the dark sector serves as a restrictive portal, allowing DM to decay/annihilate to light leptons, but not into (unobserved) protons and anti-protons. Dark sectors can also naturally induce an $\mathcal{O}(100)$ keV mass splitting between the DM states [2, 3]. Consequently, if the fields mediating the scattering of DM with atomic nuclei couple off-diagonally to different DM states, the result is a novel inelastic recoil spectrum [9] which has been used to explain the DAMA results [10]. Indeed, regardless of any DAMA signal, inelastic scattering is a generic consequence of dark sectors which can be probed by upcoming experiments.

The phenomenology summarized above follows from the connection between GeV-scale fields and the Standard Model (SM). But this is unlikely to be the whole story, because we would like the TeV-scale mass of DM to be related to the scale of electroweak symmetry breaking. The simplest way to generate the mass of DM is to couple it to a singlet that also couples to the SM-Higgs and receives a TeV-scale VEV [3, 11]. This naturally allows DM to scatter elastically off of atomic nuclei via the exchange of a Higgs/singlet. *We find that such dark sector models yield a distinct recoil spectrum, with both elastic and inelastic components, visible at the next generation of direct detection experiments such as XENON100.*

This paper is structured as follows. In Sec. II we introduce this new recoil spectrum and survey its unique features. In Sec. III we construct an explicit NMSSM-like model realizing the scenario we propose, and discuss the constraints imposed on it from considerations of the relic density. In Sec. IV we discuss the masses and couplings of the model in a convenient limit, and present several benchmark points. Sec. V contains our conclusions.

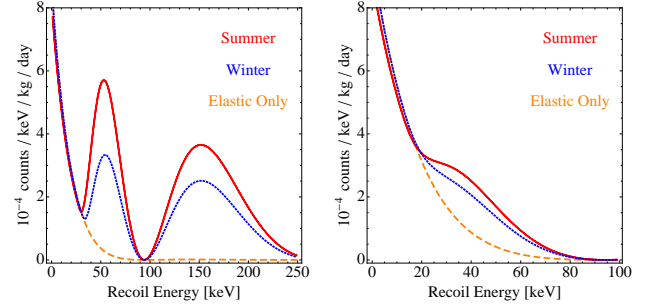


FIG. 1: Sample semielastic recoil spectra with Xenon, corresponding to the two benchmark models of Section IV. We have assumed a local DM density of $\rho = 0.3$ GeV/cm³, and DM velocities are taken to follow a truncated Maxwell-Boltzmann distribution with $v_0^{\text{rms}} = 220$ km/sec and a cutoff of $v_{\text{esc}} = 600$ km/sec. We use the Helm nuclear form factor [12], with the parameterization of Ref. [13]. The double hump structure on the *left* results from the inelastic component of the spectrum overlapping the zero of the form factor at ~ 100 keV. The summer (winter) spectra correspond to June 2nd (December 2nd). Both spectra are consistent with current limits [14, 15] and predict ~ 20 events in the first year of XENON100 data (within $8.7 \leftrightarrow 40$ keV).

II. SEMI-ELASTIC SCATTERING

The elastic scattering of DM with atomic nuclei can be a natural consequence of the mechanism setting its TeV-scale mass. We will illustrate this in an especially simple setup by coupling DM and the Higgs to the same singlet field. While we will work in a supersymmetric framework, our results are easily generalized to other scenarios.

Consider the superpotential

$$W = \lambda S H_d \cdot H_u + \eta S \chi \bar{\chi}, \quad (1)$$

where H_d and H_u are the two Higgs doublet fields, S is the NMSSM singlet [16], and $\chi/\bar{\chi}$, which are oppositely charged under a dark sector gauge symmetry, will compose our DM candidate. After electroweak symmetry breaking, S receives a VEV, which generates a supersymmetric mass for the DM fields, $m_\chi = \eta \langle S \rangle$. Taking DM to be a scalar component of $\chi/\bar{\chi}$ (we will justify this assumption in the next section), we see that the F -term

potential includes a direct coupling between DM and the Higgs, $|F_S|^2 \supset \chi \bar{\chi} H_u^* H_d^* + \text{h.c.}$ This coupling allows the Higgs to mediate the elastic scattering of DM against nuclei. A second contribution to elastic scattering is mediated by the singlet S , which mixes with the Higgs after electroweak symmetry breaking.

At the same time, other dark sector interactions can lead to an inelastic component of scattering. We consider the class of models where DM is charged under a GeV scale dark sector, with a $U(1)_d$ gauge factor that kinetically mixes with hypercharge,

$$\mathcal{L} \supset \frac{\epsilon}{2} B^{\mu\nu} b_{\mu\nu} + g_d b^\mu (\chi_0 \partial_\mu \chi_1 - \chi_1 \partial_\mu \chi_0). \quad (2)$$

Here $\chi_{0,1}$ are the two real scalar components of DM separated by a small mass splitting of order $\delta \sim 100$ keV, B_μ and b_μ are the hypercharge and $U(1)_d$ gauge fields, and ϵ parameterizes the size of the kinetic mixing. The mass splitting can be generated by a higher dimension operator [6], or radiatively by the breaking of a non-Abelian dark sector gauge symmetry [5]. Through kinetic mixing, the dark sector photon, b_μ , acquires ϵ -suppressed couplings to quarks and thereby mediates inelastic scattering between DM and nuclei. This scattering will take place along with the elastic scattering described before, realizing a scenario we term *semielastic* scattering [27].

Phenomenologically, semielastic DM can be parameterized by the 4 parameters, m_{χ_0} , δ , σ_E , and σ_I . The elastic scattering (σ_E) dominates at low nuclear recoil energy while the inelastic scattering (σ_I) dominates at higher recoil energy. Examples of such a spectrum are shown in Fig. 1. The unique spectral shape changes the constraints and reach, in the (σ_E, m_{χ_0}) plane, as shown in Fig. 2. We do not attempt to fit the possible DAMA signal [10].

III. MODEL

We now provide an explicit realization of the scenario described above. We take as our starting point the NMSSM, where a singlet superfield S couples to the two Higgs multiplets of the MSSM. To this, we add an additional coupling of the singlet to DM, as in Eq. 1, and a $U(1)_d$ dark sector along the lines of Refs. [6, 18].

In detail, we will be concerned with the following terms in the superpotential,

$$W \supset \lambda S H_d \cdot H_u + \eta S \chi \bar{\chi} + \frac{1}{3} \kappa S^3 + \rho N R \bar{R} + \frac{1}{\Lambda} \chi^2 \bar{R}^2 \quad (3)$$

where H_d and H_u are the two Higgs doublet fields, S is the NMSSM singlet, χ and $\bar{\chi}$ will compose our DM candidate, R and \bar{R} are GeV-scale dark sector Higgs fields, and N is a GeV-scale singlet whose presence insures that all dark sector fields receive a tree-level mass [6]. We will see below that the higher-dimension operator, suppressed by $\Lambda \gtrsim 10$ TeV, will generate a small DM mass splitting.

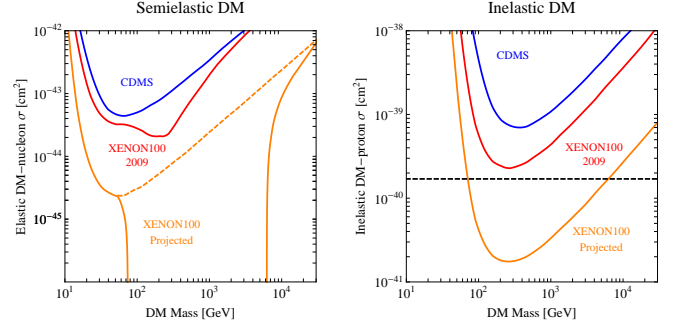


FIG. 2: The *left* panel shows the current 90% limits, from CDMS [14] and XENON100 [15], on the semielastic scenario in the DM mass - elastic cross-section plane. We have fixed the DM splitting, $\delta = 140$ keV, and inelastic cross-section, $\sigma_I = 1.7 \times 10^{-40}$ cm² per proton, to match the second benchmark of Section IV. We have also included the projected limit from XENON100 after one year of data, assuming zero background, a raw exposure of 6000 kg \times days, an efficiency of 38%, and a nuclear recoil energy range of 8.7 to 40 keV. The prominent dip in cross-section indicates the range of masses where the model will be visible from inelastic scattering alone (the dashed orange curve shows the limit without inelastic scattering). This can be seen on the *right* panel which shows the current and projected limits on inelastic scattering only, with $\delta = 140$ keV. The black (dashed) horizontal line on the right corresponds to the inelastic cross-section assumed on the left.

We assign χ and R ($\bar{\chi}$ and \bar{R}) charge 1 (-1) under a dark $U(1)_d$ gauge group. Furthermore, we assume the presence of supersymmetric kinetic mixing,

$$\mathcal{L} \supset -\frac{\epsilon}{2} \int d^2\theta W_Y W_b, \quad (4)$$

for W_Y and W_b , the hypercharge and dark supersymmetric field strengths, where $\epsilon \sim 10^{-4} \leftrightarrow 10^{-5}$ is naturally generated, at one loop, by integrating out physics at higher energy scales. Expanding in components, the kinetic mixing includes D-term mixing, which generates an effective Fayet-Iliopoulos D-term in the hidden sector at the GeV scale [5, 6].

Upon minimizing the dark sector potential one finds that R_c develops a VEV $\langle R_c \rangle \equiv v_r \sim \text{GeV}$ which Higgses the dark photon, giving it a mass $m_{\gamma_d} = g_d v_r$. The other light dark sector states also live at the GeV-scale. Finally, we note that there can be $\mathcal{O}(1)$ corrections to their masses coming from SM SUSY breaking, which is communicated to the dark sector through gauge interactions with χ acting as a messenger. These corrections have been included in our benchmark spectra of section IV, although they have no qualitative effect on the phenomenology.

We now consider the spectrum of the χ multiplet, which will contain DM. After S gets a VEV, there are two nearly degenerate fermionic states with masses $\sim \eta v_s / \sqrt{2}$ (these states are split a small amount by the higher-dimension operator). Meanwhile, the scalar components are split from their supersymmetric masses by

$\langle F_S \rangle$, and under the assumption that χ 's dominant source of SUSY breaking is communicated by S , we can neglect additional soft terms. The four scalar degrees of freedom divide into two pairs with masses above and below the fermions, separated by a large weak-scale splitting,

$$m^2 = \eta \left[\frac{v_s^2}{2} (\eta \pm \kappa) \mp \frac{\lambda}{4} v_{EW}^2 \sin(2\beta) \right], \quad (5)$$

where v_s is the singlet VEV. Within each scalar pair there is a smaller splitting

$$\delta m^2 = \sqrt{2} \eta \frac{v_s v_r^2}{\Lambda} \quad (6)$$

where v_r is the VEV of the dark Higgs. In what follows, we will label the scalar mass eigenstates χ_i for $i : 0 \rightarrow 3$ in order of ascending mass. The lightest state, χ_0 , will serve as our DM candidate, and $\delta m = m_{\chi_1} - m_{\chi_0} \sim 100$ keV is a consequence of Eq. 6.

Now, demanding that this model reproduce the observed relic abundance of dark matter places strong constraints on the different couplings and VEVs. DM can annihilate via three competitive channels: (1) to Higgses and singlets, (2) via dark sector gauge interactions, and (3) to dark sector Higgses through the higher-dimension contact interaction of Eq. 3. DM has the observed relic density if these channels sum to have the correct annihilation rate for a thermal relic,

$$\langle \sigma v \rangle \sim 2.5 \times 10^{-9} \text{ GeV}^{-2}. \quad (7)$$

We derive constraints on the model by demanding that no individual channel exceed this rate. To derive these limits, it is sufficient to consider self-annihilations of χ_0 . In general, there is also co-annihilation of χ_0 with χ_1 (and the $\tilde{\chi}$ fermions for small enough $\langle F_S \rangle$), but the following estimates still apply up to $\mathcal{O}(1)$ corrections. We do not consider constraints on Sommerfeld enhanced annihilations from cosmology [19]. Our limits are therefore conservative and also applicable to decaying DM models [8].

First we consider DM annihilations into the SM Higgses. Assuming these are light compared to m_χ , one finds their contribution to the annihilation rate to be

$$\langle \sigma v \rangle \gtrsim \frac{1}{8\pi} \left(\frac{5m_{\chi_0}}{v_s^2} \right)^2 + \frac{\lambda^4}{2\pi m_{\chi_0}^2} \quad (8)$$

which implies

$$v_s \gtrsim 4.5 \text{ TeV} \left(\frac{m_{\chi_0}}{1 \text{ TeV}} \right)^{1/2}. \quad (9)$$

While there are also constraints on λ , they are far less severe:

$$\lambda \lesssim 0.4 \left(\frac{m_{\chi_0}}{1 \text{ TeV}} \right)^{1/2}. \quad (10)$$

DM can annihilate through dark sector gauge interactions with rate,

$$\langle \sigma v \rangle \sim \frac{g_d^4}{8\pi m_{\chi_0}^2} \quad (11)$$

which constrains the dark gauge coupling:

$$\left(\frac{g_d}{0.5} \right)^2 \left(\frac{1 \text{ TeV}}{m_{\chi_0}} \right) \lesssim 1. \quad (12)$$

In addition, the non-renormalizable operator that generates the small DM splitting allows DM to annihilate into pairs of dark-Higgses,

$$\langle \sigma v \rangle \sim \frac{(\delta m_{\chi_0})^2}{8\pi v_r^4}. \quad (13)$$

Therefore, we find a non-trivial constraint relating the mass splitting between the dark matter states and the dark sector breaking scale [8],

$$\left(\frac{\delta m_\chi}{100 \text{ keV}} \right) \left(\frac{1 \text{ GeV}}{v_r} \right)^2 \lesssim 1 \quad (14)$$

We conclude this section with a brief discussion of other important constraints on this model. We note that the excited state χ_1 is long-lived and has a relic density that is constrained by inelastic down-scattering, but its density can be depleted in several ways as discussed by Ref. [20]. There are a number of additional constraints if one attempts to explain the cosmic ray anomalies through Sommerfeld enhanced annihilations as in Refs. [2, 4]. Dark matter can annihilate into hidden sector gauginos which decay to a dangerous amount of SM photons as discussed by [8]. This constraint is alleviated if $m_{\text{gravitino}} \gtrsim 1$ GeV, or by considering a more elaborate dark sector. There is tension from astrophysical limits on neutrinos and photons from final state radiation, coming from the galactic center [21]. Alternatively, these astrophysical tensions are alleviated if the cosmic rays are produced by DM decays into the dark sector [8].

IV. BENCHMARKS

It is convenient to consider this model in the various analytically tractable limits of the NMSSM. One finds, however, that whether one starts with a small κ (the PQ-symmetric limit [22]) or with small A -terms (the R-symmetric limit [23]), the requirement of a sizable v_s , a stable EWSB minima, and an elastic recoil spectra visible at current direct detection experiments necessitates small κ and λ . We therefore consider the limit $\kappa, \lambda \rightarrow 0$.

DM scatters elastically by exchanging the three CP-even Higgses, s , h , and H . With DM at the TeV scale and the three scalar Higgs masses above 100 GeV, we find that it will be difficult to see the elastic scattering at current direct detection experiments. Things become

TABLE I: Benchmark points for semielastic scattering. Here m_s is the mass of the lightest CP-even scalar, which tends to dominate the elastic scattering rate. The first benchmark has a DM mass that can explain the cosmic ray anomalies with annihilations ($m_{\chi_0} \sim 1$ TeV), while the second benchmark has a mass appropriate for decaying DM ($m_{\chi_0} \sim 2$ TeV) [21].

λ	η	κ	$\tan\beta$	A_κ	A_λ	v_s	g_d	ϵ	m_{χ_0}	δm_χ	m_s	σ_E (per nucleon)	σ_I (per proton)
0.025	0.20	0.0060	15	-110 GeV	300 GeV	7 TeV	0.5	$2 \cdot 10^{-4}$	975 GeV	203 keV	14 GeV	$1.7 \cdot 10^{-43} \text{ cm}^2$	$8.3 \cdot 10^{-39} \text{ cm}^2$
0.015	0.40	0.0015	10	-15 GeV	20 GeV	8 TeV	0.6	$3 \cdot 10^{-5}$	2259 GeV	140 keV	12 GeV	$4.3 \cdot 10^{-43} \text{ cm}^2$	$1.7 \cdot 10^{-40} \text{ cm}^2$

more interesting if one of these states is light, enhancing the elastic cross-section. The mostly-singlet scalar, s , enjoys suppressed couplings to the electroweak gauge bosons and can be very light without conflicting with existing LEP limits [24]. We work in the limit where $m_s \lesssim 50$ GeV. One finds

$$\sigma_{\text{el}} \sim 1.7 \cdot 10^{-40} \text{ cm}^2 \left(\frac{m_{\chi_0}}{v_s} \right)^2 \left(\frac{g_H \alpha_H + g_h \alpha_h}{m_s^2} \right)^2 \quad (15)$$

where $g_h \sim 1$ and $g_H \sim \frac{1}{2}(\tan\beta - \cot\beta)$ parameterize the couplings of h and H to nucleons [25] (we use the nuclear matrix elements of Ref. [26]), and α_h/α_H denote the singlet-Higgs mixing angles. Note that while it seems one can arbitrarily increase σ_E via g_H by choosing a large $\tan\beta$, the singlet proportionally decouples from H , so no such tuning is possible.

We present 2 benchmark points in Table I. Both yield the correct relic abundance and a recoil spectrum visible in one year of XENON100 data.

V. DISCUSSION

Here we have studied a mechanism that naturally relates the mass of DM to the scale of electroweak symmetry breaking in models with a GeV-scale dark sector. DM scatters against nuclei elastically via a Higgs/singlet, and inelastically through dark gauge boson exchange. Com-

bined, the spectrum has a unique semielastic shape which can be discovered in upcoming direct detection experiments such as XENON100.

While our primary concern has been the unique recoil spectrum particular to this class of models, we found in Sec. III that the parameters are constrained, nontrivially, by the requirement of getting the right relic density. It would be interesting to further investigate the interplay between these constraints and the modified Higgs phenomenology of the NMSSM.

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